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Doppler Evaluation of Decompression Tables

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I. INTRODUCTION

The Doppler ultrasonic bubble detector, which enables the detection of moving gas bubbles in the circulatory system, is a valuable tool for the evaluation of decompression tables and profiles. Traditionally, the absence of clinical symptoms of decompression sickness (DCS) has been taken to be the ultimate indicator of safety. From a statistical point of view, however, proving the safety of dives using the binary outcome of DCS vs. no DCS with any reasonable degree of confidence would require

many more dives than are normally feasible (See also Weathersby in this book). Moreover, the diagnosis of DCS can be quite subjective. Gas bubbles in the circulatory system occur far more frequently than DCS and bubbles can be detected even in safe dives. The Doppler ultrasonic bubble detector provides far more information than DCS to assist in the assessment of the severity of dive profiles. In this paper, the technique of bubble monitoring and the classification of bubble signals will be described and the use of Doppler monitoring in bounce or non-saturation diving will be discussed. Only the application to manned diving will be considered.

The Doppler ultrasonic bubble detector is based on equipment originally developed for the measurement of blood flow. Bubbles are much stronger reflectors of ultrasound than the normal components of the blood, and therefore can be easily detected against the background signal from the blood. The Doppler ultrasonic flowmeter was first used for detecting circulating decompression gas emboli in the larger arteries and veins of sheep by Spencer and Campbell (1968). The first detection of bubbles in human divers, although unrecognized at the time, was in 1968 by Spencer and continuing work on human monitoring led to the development of the Spencer Precordial Transducer in 1970, an instrument specifically designed for decompression monitoring. A scheme for classifying the bubbles was developed by Spencer and Johanson (1974) and Spencer (1976).

The Doppler ultrasonic bubble detector was, at one time, believed to have potential as a personal decompression monitor where the individual could listen to his own bubbles and control his own decompression. It soon became evident that this was not practical because detectable bubbles in most non-saturation dives occurred after the surface was reached. It was only during severe dive profiles, in which a substantial amount of time was spent at the decompression stops (e.g., exceptional exposure dives), that bubbles were able to be detected at the decompression stops (Neuman *et al.*, 1976). In addition, the training required for identifying and classifying bubbles was too great to make it practical for the ordinary diver to be able to detect bubbles and control the decompression. Thus, Doppler is now recognized as being a tool primarily for post-dive analysis.

Since the early work of Spencer (1977), several other investigators have done extensive research in applying Doppler monitoring to a variety of decompression applications and in advancing the state of Doppler monitoring for manned decompression studies. For example, Masurel at the Centre dÉtudes et de Recherches Techniques Sous-Marines (CERTSM) and others in France used Doppler extensively for animal and human dives, both non-saturation and saturation (Masurel, 1987). In 1978, Kisman of the Defence and Civil Institute of Environmental Medicine

(DCIEM) and Masurel developed an alternative classification scheme for identifying and grading bubbles (Kisman *et al.*, 1978). From 1979 to 1985, DCIEM used Doppler for evaluating air decompression profiles (Nishi *et al.*, 1981) and applied the method to developing a new set of air decompression tables (Nishi, 1987). Doppler information was used to supplement the information obtained using the traditional method of DCS vs no DCS.

The main purpose in using Doppler, therefore, is to obtain comparative information, post-dive, to assist in determining whether or not a table or profile is safe or hazardous by determining the quantity and duration of bubbles resulting from that profile. The normal method for detecting venous gas emboli is to listen to the signal from the Doppler ultrasonic bubble monitor and to identify and classify the bubbles according to some classification scheme such as the Spencer code or the Kisman-Masurel (KM) code. Consistent and reliable bubble identification and grading require highly skilled and well-trained observers. The signal in the precordial region is extremely busy, with contributions from the blood flow, heart valves, and heart wall motion. Because human judgement is required, the interpretation of the signal can vary to some extent among observers; however, identification and classification of bubbles are still best done by human observers. Although there are some problems with subjectivity, human observers are more accurate overall for assessing bubbles in the precordial region than are automatic bubble detection systems.

II. DOPPLER MONITORING PROCEDURES

In order to provide a means for comparing results between different researchers and users of Doppler equipment, standardized procedures for monitoring dive subjects and identifying and classifying bubbles are required. Fortunately, the existing procedures and classification systems are similar enough that such comparisons can be made. The following describes a recommended standardized monitoring procedure. They are based on procedures used at DCIEM (Eatock and Nishi, 1986).

A. Doppler Hardware

The instrument used should be a simple continuous-wave (CW) Doppler ultrasonic device operating at 5 or 2.5 MHz developed specifically for detecting bubbles. CW Doppler instruments developed for clinical use tend to lack sensitivity and durability. The instruments should be readily available, relatively inexpensive, easy to use, provide a good signal, and

be reliable. Three CW precordial Doppler ultrasonic bubble detectors which are specifically designed for the hyperbaric environment are commercially available (Appendix A). These are manufactured by the Institute of Applied Physiology and Medicine (IAPM), Sodelec S.A., and Techno Scientific Inc. (TSI). Although the transducers are designed primarily for monitoring the precordial region (either the pulmonary artery or the right ventricle of the heart), other veins, such as the subclavian, the femoral, or the inferior vena cava can also be monitored to provide supplementary information. Monitoring is done by trained observers listening to the signals through headphones.

B. Monitoring Sites

Only moving intravascular bubbles can be found with the Doppler method. The primary site to be monitored should be the right ventricle (the precordial site) since an estimate of the rate of bubble production for the entire venous system can be obtained (assuming that the bubbles persist long enough to reach the heart). An alternative is the pulmonary artery. To supplement observations from the precordial site, the subclavian veins (both left and right shoulders) can be monitored. Bubble signals at these sites are unambiguous; however, they should not be used as an alternative to the precordial site because they do not cover the whole body.

C. Subject Position

The subject should be standing or lying down for the evaluation. Either position produces good results, so the choice can be dictated by convenience. The evaluations should be done for two conditions — one with the subject at rest, and the other after the subject has moved in some defined way. For the precordial evaluation, a standing subject would do a deep knee-bend — squatting down and standing up, in a smooth, continuous motion. For the subclavian site, the subject would clench his fist. The movement case is useful because it often produces a shower of bubbles that are easily identifiable.

D. Frequency of Monitoring

The objective in monitoring the diver is to obtain a history of the bubble evolution or production for each subject in the dive. Depending on the severity of the dive profile, bubbles are often not detected immediately after a diver surfaces, but start some time after. For some divers, delays of an

hour or more have been observed before bubbles were detected, but in most cases, bubbles tend to start earlier and peak about an hour after surfacing. Bubbles can persist for several hours after a severe dive. As it is not generally possible to monitor the divers continuously, the divers must be monitored periodically at some set time interval. For most non-saturation dives, monitoring should begin soon after the divers reach the surface and should be repeated at 30 to 40 min intervals for at least two hours. The exact time interval will depend on the number of divers being monitored and the profile being evaluated.

III. BUBBLE CLASSIFICATION METHODS

Identification and classification of bubbles should be according to the Kisman-Masurel (KM) method (Eatock and Nishi, 1986; Hjelle *et al.*, 1987; Kisman *et al.* 1978) or the Spencer method (Spencer and Johanson, 1974; Spencer, 1976). Both methods give similar results but it is believed that the KM method is easier to learn and use and gives a better representation of the bubble signal.

A. The Kisman-Masurel Code

The KM Code for classifying bubbles consists of three parameters which are used to describe the bubble signal (Tables 1, 2, and 3). By breaking down the bubble signal into these component parts, it is much easier to identify the bubbles and to classify them. The KM code can be used for both the rest and movement conditions. Each parameter is assigned a classification from 0 to 4. These parameters are combined to give a single bubble grade (Table 4) similar to that derived from the Spencer code but with a greater graduation.

The first parameter, frequency (f), represents the number of bubbles per cardiac period (Table 1). For code 4, the bubbles are so numerous that they cannot be individually distinguished.

TABLE 1.

Frequency Parameter

Code	Frequency (f) — bubbles per cardiac period
0	0
1	1 - 2
2	several 3 - 8
3	rolling drumbeat 9 - 40
4	continous sound

The second parameter differs for the two monitoring conditions — rest and movement (Table 2). For the rest condition, it represents the percentage (p) of cardiac periods having a specified bubble frequency (i.e., the first parameter from Table 1). For the movement condition, it represents the number of successive cardiac periods (d) having at least a specified bubble frequency following the movement. The first such period must occur within 10 heart beats following the movement.

TABLE 2.

Percentage/Duration Parameter

Code	Rest Percentage (p)	Movement Duration (d) Cardiac Periods
0	0	0
1	1 - 10	1 - 2
2	10 - 50	3 - 5
3	50 - 99	6 - 10
4	100	>10

The third parameter, shown in Table 3, is the amplitude of the bubble signal (A(b)) which is compared to the amplitude of the normal cardiac sounds (A(c)).

TABLE 3.

Amplitude Parameter

Code	Amplitude (A)			
0	no bubbles discernible			
1	barely perceptible,	A(b)	<<	A(c)
2	moderate amplitude,	A(b)	<	A(c)
3	loud,	A(b)	~	A(c)
4	maximal,	A(b)	>	A(c)

The three parameters are combined in the form 'fpA' for the rest case and 'fdA' for the movement case to give the KM code for each assessment. This KM code is reduced to a single bubble grade (bg) according to Table 4. It is recommended that bubble grades be represented as Roman numerals

rather than Arabic numerals to emphasize that these grades represent classifications and not numbers and that standard statistical analyses can not be used (Gatock and Nishi, 1987). It should be noted that some combinations of the KM code will never occur and some others are rarely seen. For example, 144 and 411 are physically impossible.

TABLE 4.

KM Codes vs. KM Bubble Grades

fpA/fdA	bg	fpA/fdA	bg	fpA/fdA	bg	fpA/fdA	bg
111	I–	211	I–	311	I	411	II–
112	I	212	I	312	II–	412	II
113	I	213	I+	313	II	413	II+
114	I	214	II–	314	II	414	III–
121	I+	221	II–	321	II	421	III–
122	II	222	II	322	II+	422	III
123	II	223	II+	323	III–	423	III
124	II	224	II+	324	III	424	III+
131	II	231	II	331	III–	431	III
132	II	232	III–	332	III	432	III+
133	III–	233	III	333	III	433	IV–
134	III–	234	III	334	III+	434	IV
141	II	241	III–	341	III	441	III+
142	III–	242	III	342	III+	442	IV
143	III	243	III	343	III+	443	IV
144	III	244	III+	344	IV–	444	IV

B. The Spencer Code

The Spencer code is used for precordial signals with the subject breathing quietly and otherwise motionless in a sitting or supine position. The bubbles are classified on a scale from 0 to 4 as shown in Table 5.

A comparison of the Spencer and the KM Codes shows that the two systems are similar, with the Spencer Code being a subset of the KM Code. Table 6 gives the equivalent KM Codes and bubble grades which correspond to the Spencer grades.

TABLE 5.

Spencer Scale for Grading Bubbles

Grade	Description
0	A complete lack of bubble signals.
I	An occasional bubble signal discernible with the cardiac motion signal with the great majority of cardiac periods free of bubbles.
II	Many, but less than half, of the cardiac periods contain bubble signals, singly or in groups.
III	All of the cardiac periods contain showers of single-bubble signals, but not dominating or overriding the cardiac motion signals.
IV	The maximum detectable bubble signal sounding continuously throughout systole and diastole of every cardiac period, and overriding the amplitude of the normal cardiac signals.

TABLE 6.

Correspondence between Spencer and KM Codes

Spencer Grade	KM Code (Bubble Grade)
I	111 (I –), 112 (I), 113 (I) 211 (I –), 212 (I), 213 (I +)
II	121 (I +), 221 (II –), 122 (II), 222 (II) 123 (II), 223 (II +)
III	242 (III), 342 (III +), 243 (III), 343 (III +)
IV	444 (IV)

The advantage of the KM Code is that it allows greater scope for classifying the bubble signal and allows for the movement condition. Although the KM code appears to be complex and more difficult than the Spencer code, it is believed that it is an easier system to learn because the classification is done in a systematic step by step manner. With experience, the breakdown into the three parameters can be done simultaneously. Proficiency in classifying bubbles according the KM code can be reached in considerably less time than with the Spencer code.

IV. BUBBLES AS INDICATORS OF DECOMPRESSION STRESS

Doppler-detected bubbles are not normally believed to be the cause of DCS, but their presence in the circulation may be indicative of bubbles elsewhere in the body. Large numbers of bubbles are not necessarily accompanied by DCS, nor do they directly lead to observable symptoms of DCS. However, incidents of DCS are generally accompanied by bubbles; hence,the risk of DCS does appear to be increased. Furthermore, there is some evidence that intravascular bubbles may cause subclinical damage that may have long-term effects; thus dives which produce many bubbles should be avoided (Eckenhoff, 1985).

A. Bounce or Sub-Saturation Diving

There have been several surveys of Doppler data which have shown a relationship between intravascular bubbles and DCS (Eatock, 1984; Vann *et al.*, 1982). Unfortunately, many of these have tended to combine data from a variety of sources such as air dives, helium-oxygen dives, and nitrox dives. A study of 2,483 subject-dives done at DCIEM since 1972 shows that the correspondence of DCS with bubbles depends on the breathing gas and whether or not oxygen was used during the decompression. Tables 7, 8, and 9 show the percentage of DCS events vs. bubble grades for these dives. All dives were done in a hyperbaric chamber with both dry and wet subjects.

Table 7 shows the results for 921 subject-dives on compressed air only. These dives were mostly taken from studies to determine safe diving limits using the DCIEM Kidd-Stubbs decompression computer model (Nishi *et al.*, 1981), to determine no-decompression limits for compressed air (Nishi *et al.*, 1982), and to develop a new set of air decompression tables (Nishi, 1987). The number of subjects observed with the given bubble grades at rest and after movement are shown, along with the number of subjects incurring DCS for each bubble grade. It can be seen that subjects having Grade II bubbles or greater have a higher risk of DCS. Three type II DCS were associated with Grade II bubbles at rest. Grade IV bubbles at rest are relatively rare; hence, the small number of subjects with this level. However, there is evidence to suggest that the risk of DCS will be extremely high with Grade IV bubbles. For example, Spencer and Johanson (1974) reported 2 out of 3 with DCS, and Neuman *et al.* (1976) reported 6 of 19 with DCS.

Table 8 shows the results for 701 compressed air dives with oxygen used during decompression and nitrox dives with a higher percentage of oxygen than compressed air. Most of these dives were conducted during

TABLE 7.

Correspondence between Precordial Bubbles and DCS for Compressed Air Dives

	At Rest					After Movement				
Bubble Grades	0	I	II	III	IV	0	I	II	III	IV
No. of Subjects (921)	666	84	79	90	2	599	86	64	147	25
No. with DCS (27)	2	0	4	20	1	1	1	3	17	5
Percent Incidence	0.3	0.0	5.1	22.2	50.0	0.2	1.2	4.7	11.6	20.0

the development of the DCIEM compressed air tables (Nishi, 1987) for in-water oxygen decompression where oxygen was breathed at 9 msw until the decompression requirements were completed and for surface decompression with oxygen where the subjects surfaced from the 9 msw stop and then recompressed to 12 msw on oxygen to complete the decompression requirements. The results are not as clear-cut as for those air dives where oxygen was not used during decompression. Five DCS cases occurred without any observable precordial bubbles at rest or after movement. However, it should be noted that in cases where no bubbles were observed precordially and DCS symptoms occurred in the shoulder or arm, bubbles were often observed in the subclavian vein on the same side as the symptoms. It is also possible that bubbles could have existed in other parts of the body. No Grade IV bubbles were observed in these dives. Of three Type II DCS, one was associated with no observable bubbles, one was associated with Grade II bubbles at rest, and the third had Grade III bubbles at rest.

TABLE 8.

Correspondence between Precordial Bubbles and DCS for Air with Oxygen Decompression and Nitrox Dives

	At Rest					After Movement				
Bubble Grades	0	I	II	III	IV	0	I	II	III	IV
No. of Subjects (701)	517	45	73	66	0	487	34	37	131	0
No. with DCS (14)	9	0	3	2	0	5	2	2	5	0
Percent Incidence	1.7	0.0	4.1	3.0	—	1.0	5.9	5.4	3.8	—

Table 9 shows the results for 861 helium-oxygen dives. These include breathing mixtures with 80% He and 84% He, and some dives with a semi-closed circuit breathing apparatus with a variable level of helium. Some dives in this set used the US Navy Partial Pressure Tables with oxygen decompression at 15 and 12 msw. Most were experimental dives from the current DCIEM program to develop a new set of helium tables as a replacement for the USN tables. Decompression from these dives include those using oxygen decompression at 9 msw, using air decompression from the first stop followed by oxygen decompression at 9 msw, using air decompression all the way to the surface, and using surface decompression with oxygen. The results show that the risk of DCS with Grade III bubbles is also much lower than for air.

TABLE 9.

Correspondence between Precordial Bubbles and DCS for Helium/Oxygen Dives

	At Rest					After Movement				
Bubble Grades	0	I	II	III	IV	0	I	II	III	IV
No. of Subjects (861)	565	42	89	162	3	522	20	47	205	67
No. with DCS (16)	5	0	1	9	1	5	0	0	7	4
Percent Incidence	0.9	0.0	1.1	5.6	33.3	1.0	0.0	0.0	3.4	6.0

A number of other sources exist for comparing the results of Doppler bubble detections with observed incidences of DCS. For example, the work done by Spencer and Johanson (1974) and Spencer (1976) on no-decompression dives provides some valuable comparisons (Table 10).

TABLE 10.

Bubbles vs. DCS for Compressed Air Dives Precordial Bubbles at Rest (from Spencer)

Bubble Grades	0	I	II	III	IV
No. of Subjects (124)	105	25	16	13	3
No. with DCS (11)	1	1	3	6	2
Percent Incidence	1	4	19	46	67

In these experiments, some subjects were put on surface oxygen or recompressed for oxygen therapy if bubble grades were too high or started soon after surfacing. The DCS cases in the table are for symptoms of pain only and do not include those divers without symptoms who were treated. Thus, it is uncertain whether these divers would also have incurred DCS if left untreated. However, the trend for greater risk of DCS with higher bubble grades can clearly be seen.

Powell and Johanson (1978) reported on the use of helium or neon as the breathing gas. They found a difference between the results for divers using no oxygen breathing during the final decompression stops and those using oxygen. In the first group, divers displaying Grade III or IV bubbles had a considerably greater probability of developing DCS than those with Grade I or II bubbles. Almost 2/3 of those with the higher bubble grades developed some form of DCS. In the second group, problems were not encountered in the divers until Grade IV bubbles were detected, and they concluded that divers with Grade III bubbles or less would be unlikely to encounter DCS. They postulated that the presence of elevated arterial oxygen tension allowed the tissues to tolerate a greater degree of embolization in the microcirculation.

Nashimoto and Gotoh (1977, 1978) studied 152 caisson workers and found that bubble signals were associated with 40 out of 49 workers with DCS (itches, bends and chokes). Bubble signals were heard in 48 of 103 workers without DCS. The results show that 79% of skin itches were associated with bubbles and all cases of bends and chokes were associated with bubbles.

TABLE 11.

Bubbles vs. DCS for Compressed Air (Caisson) Workers Precordial Bubbles at Rest (from Nashimoto and Gotoh)

Bubble Grades	0	I	II	III	IV
No. of Subjects (152)	64	35	30	22	1
Percent Itches (32)	14	29	40	5	0
Percent Bends (14)	0	11	10	32	0
Percent Chokes (2)	0	0	7	5	100

B. Saturation Diving

A considerable number of saturation dives have been monitored with the Doppler ultrasonic bubble detector, both during the final decompression

to the surface and following downward and upward excursions at depth. In saturation diving, however, the correlation between DCS and bubbles does not appear to be as strong as that for non-saturation dives. Table 12 shows a summary reported by Gardette (1979) and Gardette *et al.*, (1979) for articular or muscular pains and circulating bubbles.

TABLE 12.

Percentage of Articular and Muscular Pain vs. Precordial Bubble Grades for Saturation Dives (from Gardette)

	At Rest					After Movement				
Bubble Grades	0	I	II	III	IV	0	I	II	III	IV
No. of Subjects (162)	125	24	13	0	0	43	20	39	60	0
Percent Pain	12	29	31	—	—	5	10	23	22	—

These results showed a marked difference between bounce or no-saturation dives and saturation dives. Even with no observable precordial bubbles, there is a large risk of DCS. This apparent lack of correlation of DCS with bubbles has led some investigators to conclude that Doppler monitoring is of no use for saturation dives. However, it is evident that divers with bubbles, both at the Grade I and Grade II levels, are at higher risk than those without bubbles. Therefore, divers with such bubble scores should be kept under closer observation. Grade III bubbles at rest, although not reported by Gardette in his study, have been observed in other saturation dives. In one helium saturation dive in which DCIEM was associated, Grade III bubbles at rest resulted in Type II DCS. Others have observed that Type II DCS is often associated with large numbers of intravascular bubbles (Masurel *et al.*, 1976; Masurel *et al.*, 1977).

Masurel has recommended that corrective action be taken for helium saturation dives when high bubble levels are detected (Kisman and Masurel, 1983; Masurel, 1983). During the first part of the decompression (between 100 and 80% of the maximum depth), Grade 0 and I bubbles at rest are considered normal and require no action. With Grade II bubbles, the diver must be under close observation. For Grade III bubbles at rest, the possibility of vestibular or Type II DCS exists, and a decompression stop plus some compensation table is recommended. For Grade IV bubbles at rest, immediate recompression with a superoxygenated mixture is required because of the high probability of vestibular and Type II DCS. During the second part of the decompression (to the surface), Grade III bubbles at rest, if they persist, require the subject to breathe a superoxygenated

mixture. For Grade IV bubbles, a decompression stop or recompression together with a superoxygenated mixture is required. The action taken may be modified depending on the observations made on the other divers in the same dive. Masurel has used his observations of high bubble scores to interrupt the decompression from a saturation dive to reduce the risk of DCS (Masurel *et al.*, 1978).

The effect of slowing down the ascent rate during the decompression was also clearly illustrated during a saturation dive done at DCIEM to 360 msw (Eatock and Nishi, 1986). The initial decompression rate of 28.4 msw/24 hrs (1.58 msw/hr with a sleep stop between midnight and 0600) was changed to 18 msw/24 hrs (1.0 msw/hr with 6 hr sleep stop) at 100 msw, and then to 0.5 msw/hr for the last 10 msw. Forty hours after leaving 360 msw, occasional bubbles were detected in one of four subjects. Eventually, all subjects had some bubbles with movement, and two had numerous bubbles (Grade III with movement). The bubbles peaked as the depth approached 100 msw. After the decompression rate was decreased to 1 msw/hr the number of bubbles gradually diminished until on the second day after the decrease in rate, no bubbles could be detected. However, bubbles were observed again in one of the subjects as the 10 msw depth approached. Following the second decrease in decompression rate, no more bubbles were detected. This is in contrast to similar dives done at the Norwegian Underwater Technology Center (Hjelle *et al.*, 1987). The decompression rate from 350 msw was 27 msw/24 hrs until 14 msw. Eighteen subjects were involved. By the time 100 msw was reached, 7 of the subjects had Grade III bubbles after movement. By the last day of decompression, four divers had precordial Grade III bubbles at rest and 15 divers had Grade III following movement. No Grade IV bubbles were observed in any of the divers. Seven of the divers with Grade III following movement experienced intermittent discomfort and pains in the lower limbs during the last two days of decompression; one had intense, but transient knee pains. Bubbles persisted for 3 hours after surfacing in 12 subjects and in one subject for 15 hours.

It can be seen that reducing the rate of ascent as in the DCIEM dive would have been effective in reducing the number of subjects with Grade III bubbles and most probably in eventually eliminating all observable bubbles, and eliminating the discomfort and pains felt by the subjects near the surface. Thus, for saturation dives, the results of Doppler observations can be used in real-time to reduce the risk of DCS or eliminate symptoms of discomfort and pain.

V. DISCUSSION

All the data show that, in general, the incidence of DCS is higher for the higher bubble grades and that the incidence of DCS is low when few or no bubbles are detected. Thus, for the purpose of evaluating decompression profiles, we can say that dives which produce many bubbles in a majority of the divers can be considered to be stressful with a higher risk of DCS and should be avoided. Conversely, dives which produce few or no bubbles in the majority of the divers can be considered safe. In determining criteria for the use of Doppler results for evaluating experimental or existing dive profiles and tables, it is evident that different standards must be applied depending on the breathing gas being used. For compressed air dives, most of the subjects should have only Grade 0 or Grade I bubbles. On the other hand, for helium dives, most of the subjects could have Grades 0, I or II bubbles for an acceptable profile.

Thus, simple criteria for estimating the acceptability of a table could be easily established by trying to keep the number of divers exhibiting Grades II, III and IV bubbles at rest to some percentage of the total. For example, using the figures from Table 7 for compressed air only, the expected incidence of DCS for Grades II and III combined is approximately 14%. By designing the decompression profiles so that less than 35% of the subjects have Grades II and III bubbles and none have Grade IV, it is highly likely that the risk of DCS can be reduced to less than 5%. On the other hand, for recreational divers, where the risk of DCS desired is zero, then dives which produce Grades II, III and IV bubbles should be avoided. Spencer, in his study of direct decompression after compressed air exposures (Spencer and Johanson, 1974; Spencer, 1976), concluded that safe limits require zero occurrence of severe DCS symptoms but for practical reasons some incidence of bubbles had to be accepted. He proposed a 20% occurrence of bubbles and less than 5% occurrence of mild bends pain as a reasonable compromise.

There are two factors that complicate dive table evaluation with the Doppler bubble detector. First there is considerable variation in the response among different subjects (some individuals are bubble-prone and/or bends prone) and second, individual divers can respond differently to similar dive profiles at different times. Therefore, it is necessary to use some judgement in interpreting the results.

In two series of experimental dives on compressed air, it was found that dive subjects could be divided into three groups representing high, moderate, and low "bubblers" (Nishi *et al.*, 1981). It was also found that older divers were more susceptible to having bubbles and that the majority of those who suffered DCS were high "bubblers". During the current program for

for developing helium tables, several high "bubblers" were identified and these individuals were found to be more susceptible to DCS.

If Doppler monitoring is to be used for developing safe tables, it is important that a mix of high and low "bubblers" be used as subjects. Tables developed with low "bubblers" can be hazardous for high "bubblers". Conversely, tables developed with high "bubblers" may be too conservative. It is also important that divers who are high "bubblers" and who are also prone to DCS be restricted in their diving and not be allowed to dive severe dive profiles.

There are other factors that can affect the tendency of subjects to have large levels of bubbles. For example, fatigue before a dive has been found to have a tendency to produce bubbles (Masurel, 1976). Similarly, after a dive, fatigue is usually accompanied by high bubble levels. Other factors may be the state of hydration of the subjects, obesity, age, level of fitness, infections, whether the diver may be a smoker (Gatock and Nishi, 1987), etc.

There are two main advantages to using Doppler monitoring. Doppler monitoring provides far more data than observing the incidence of DCS. For example, in the 2,483 DCIEM dives, bubbles were observed in 30%, whereas DCS occurred in only 2.3%. Therefore, not as many dives are required to establish a safe table using bubble scores than are required if DCS is the only criterion. It is often possible to use bubble observations to compare the results of two dives, even in the absence of DCS. If no bubble results were available, it would have to be concluded that there were no observed differences between the dives. The Doppler results may show that one profile will generate many bubbles in most of the subjects whereas the other may generate only a few bubbles; thus a difference between the two profiles becomes evident. In addition, in the absence of DCS and bubble results, there may be no way to determine how close to DCS threshold these dives are. It is unlikely that an experimental dive program, for example, to determine a DCS threshold, would be approved today if a high incidence of DCS were considered likely. As decompression procedures become safer, decompression testing could involve profiles that produce few or no cases of DCS, hence making the bubble results more important. In fact, with Doppler bubble monitoring, we can speak of decompression stress rather than DCS as the end point for evaluating dives. It should be noted that one need not "bend" divers to know whether or not a dive is safe.

Bubble results are more objective than DCS results. Although there is some subjectivity in classifying bubbles, well-trained observers will generally be able to identify the presence of bubbles. Success in detecting bubbles depends on the vigilance of these highly trained observers, and

although bubbles can sometimes be hard to detect, the results cannot be hidden by the diver. Divers may not report symptoms of DCS or conversely may report symptoms, because of apprehension and uncertainty, which are not directly attributable to the decompression. The main disadvantage of Doppler ultrasonic bubble detection is that it is time-consuming and labor-intensive, and demands extreme concentration for the observer.

Although this study has concentrated primarily on precordial bubbles, it is important that the results of other body sites be considered as well. For example, if all bubble results are combined from the precordial and subclavian sites, the relations between DCS and bubbles would change slightly from those of Tables 7 to 9. The number of individuals with DCS and no observable bubbles would most certainly be reduced since subclavian bubbles were observed in many of these.

In cases where DCS occurred with no observable bubbles at rest or after movement, it should also be noted that not all bubbles can be detected with the Doppler ultrasonic bubble monitor. Bubbles must be sufficiently large so that the echoes from the bubbles can be heard above the background signal of the red blood cells and other moving particles and surfaces. It has been estimated that bubbles must be approximately 80 micrometers in diameter to be detectable in the precordial region. Thus, bubbles could exist but not be detectable. In the subclavian veins, smaller bubbles can be detected because of the reduced background noise. It should again be emphasized that intravascular bubbles are not believed to be the cause of DCS. However, their presence may indicate the existence of extravascular bubbles which can cause DCS. Other body sites should be checked if possible.

One finding that warrants further study appears to be that upper body symptoms are better correlated with subclavian bubbles and that lower body symptoms are better correlated with precordial bubbles. More studies will be made of the data in the DCIEM Doppler database (which includes all 2,483 subject-dives reported here, representing over 10,000 individual monitorings) and data from other investigators which are available in compatible form. It is important that all investigators using Doppler standardize on procedures and classification methods (whether KM Code or Spencer Code) so that there is a common basis for comparing results.

VI. SUMMARY

The Doppler ultrasonic bubble detector can have an important role in the process of decompression table evaluation since it can give comparative

information on the decompression stress of the dive even in the absence of DCS. As the risk of DCS increases with increasing levels of bubbles, it is possible to assign some risk factor to dive profiles by noting the number of divers with bubbles and the levels observed. Thus ultrasonic bubble detection can give far more information than the traditional DCS vs. no DCS approach with fewer dives, and, it is not necessary to bend divers to determine if a dive profile is safe.

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APPENDIX I

Suppliers of Doppler Ultrasonic Bubble Detectors

a) Techno Scientific Inc., 60 Caster Avenue
Woodbridge, Ontario, Canada L4L 4X2

b) Sodelec, 31, Traverse Prat,
Pointe-Rouge, 13008 Marseille, France

c) Institute of Applied Physiology and Medicine
701 16th Avenue, Seattle, Washington, USA 98122